

Tamm states in electron plasma

Researchers have fabricated a voltage-tunable plasmonic crystal in a two-dimensional electron gas that operates at terahertz frequencies. *Nature Photonics* spoke to Eric Shaner, Greg Dyer and Greg Aizin about the observation of Tamm states at the crystal's edge.

■ What is a Tamm state?

Plasmonic materials support collective electron plasma oscillations. If the propagation properties of a plasmonic medium vary periodically in space, its plasmonic spectrum will exhibit a band structure when the medium is probed by light. In this sense, a plasmonic crystal is a photonic crystal formed in a plasmonic system. Breaking the translational symmetry of any crystal — be it electronic, photonic or plasmonic — gives rise to localized states in its bandgaps. Soviet physicist Igor Tamm first predicted the gap state localized at the terminated edge of a semi-infinite crystal. Tamm states differ from other surface excitations in that they are crystal states described by the complex-valued Bloch wave vector of the crystal lattice.

■ What is the motivation for investigating Tamm states?

Originally, our research was directed towards developing frequency-agile terahertz (THz) plasmonic detectors. During the course of this work, we discovered that we could directly measure the near field of resonant excitations in plasmonic microstructures. From there, we explored devices of increasing complexity by coupling sequential plasmonic resonators, eventually forming a short plasmonic crystal. Tamm states are a by-product of the finite length of the plasmonic crystal, and offer a few interesting degrees of freedom. Their localization lengths are determined by the periodicity and composition of the plasmonic crystal. Because these localization lengths are about the same as the crystal length, we could tune, and even couple, Tamm states on opposing edges of the device. This enables bandgaps to be turned on or off by electronic tuning, like a controllable photonic impurity band.

■ Tell us about your experiment.

The most significant result is the experimental observation of a voltage-tunable plasmonic crystal in a two-dimensional electron gas (2DEG) at THz frequencies, including the observation of Tamm states

at the crystal edge. A 2DEG embedded in a semiconductor heterostructure is intrinsically a type of plasmonic waveguide. In our work, we induced a spatially periodic variation in the waveguide impedance by applying a voltage to a metal terminal located above a 2DEG. We coupled THz radiation to the voltage-induced plasmonic crystals, and utilized an integrated detection mechanism to observe the resulting plasma excitations. The reconfigurability can be quite broad, and multiple voltage terminals can be used to control different sections of the 2DEG waveguide. This latter capability allowed us to observe a plasmon-induced transparency effect by controlling and coupling localized resonances in the devices.

■ What are the applications?

One possibility is the development of frequency-agile integrated photonic circuits based on plasmonic crystals. These types of structures can produce large field enhancements, and could also play a role in sensitive THz detection.

■ What was the most challenging aspect of the work?

This work required a sustained effort to develop a description of 2DEG plasma waves in an engineering formalism — a transmission line model. The equivalent photonic circuit approach has been very successful in metamaterial and metal-dielectric plasmonic research for quite some time. However, this approach has only recently gained traction in 2DEG systems.

■ Is THz plasmonics really plasmonic in nature? And, are a few periods sufficient to speak of crystals?

In contrast to metals where plasma frequencies typically lie in the ultraviolet region of the spectrum, the plasma frequencies of 2DEGs are in the far-infrared region. The fields are tightly bound around the electron plasma — the excitations are very much plasmonic. Regarding the formation of crystals with only a few periods, the main question is whether the Bloch wave vector can effectively describe wave propagation in the system. Interestingly, the formation of



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Left to right: Greg Dyer, Eric Shaner, Don Bethke, John Reno and Albert Grine at the Center for Integrated Nanotechnologies (CINT), a Department of Energy/Office of Science Scientific User Facility.

allowed bands and bandgaps requires only several repetitions of the unit cell.

■ How can the work be extended, and what are you planning to do next?

There are a variety of emerging tunable plasmonic material systems (including graphene), which cover different regions of the spectrum. A big question for us is whether these materials will have sufficiently large plasmon coherence lengths to form plasmonic crystals or even coupled resonator systems. Plasmon scattering at boundaries and interfaces, whether 2DEGs or graphene, is a major source of loss. Right now, chemical-vapour-deposited graphene has a modest plasmonic quality factor, but improvements in the growth of large-area, single-crystal graphene monolayers could lead to better tunable plasmonic materials.

INTERVIEW BY DAVID PILE

Eric Shaner and colleagues have an Article about plasmonic Tamm states in two-dimensional electron gases on page 925 of this issue.